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Energy Storage Systems Considerations for Grid-Charged Hybrid Electric Vehicles

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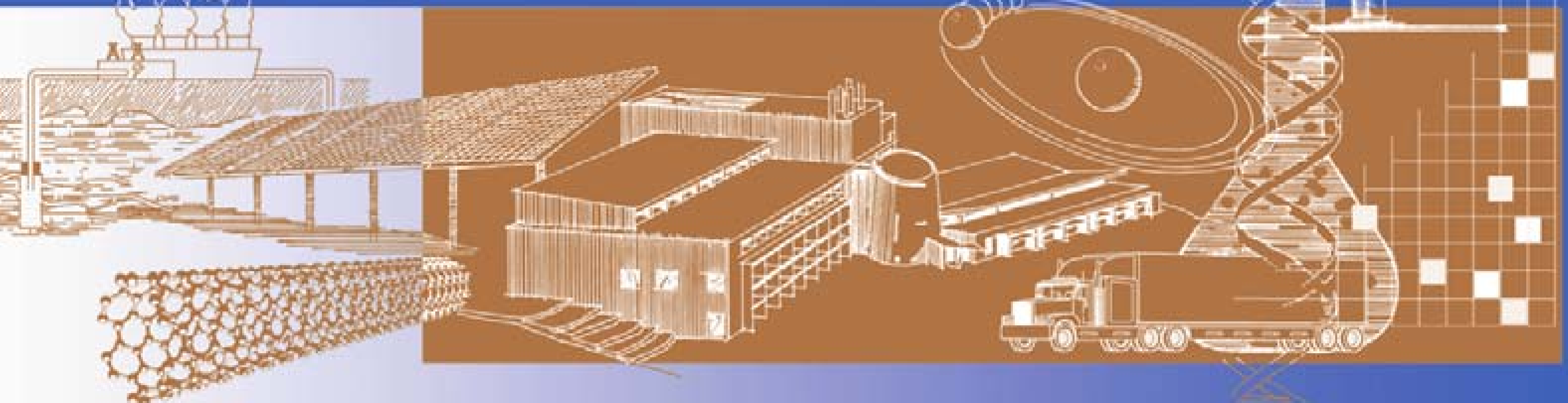

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Energy Storage Systems Considerations for Grid-Charged Hybrid Electric Vehicles

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ABSTRACT

This paper discusses battery power and energy requirements for grid-charged parallel hybrid electric vehicles (HEVs) with different operating strategies. First, it considers the traditional all-electric-range-based operating concept and shows that this strategy can require a larger, more expensive battery due to the simultaneous requirement for high energy and power. It then proposes an alternative "electric-assist" operating concept for grid-charged HEVs to enable the use of a smaller, less costly battery. However, this strategy is expected to reduce the vehicle efficiency during both charge-depleting and –sustaining operation. The paper concludes by identifying several key questions for future research.

INTRODUCTION

Grid-charged hybrid electric vehicles (HEVs) provide motorists with the option to travel a certain number of miles each year using energy sourced from the electricity grid. Relative to non-grid-charged HEVs, the potential added benefits of these vehicles include:

- Lower operating costs, since electricity costs less "per mile" than gasoline.
- Reductions in tailpipe emissions, since many miles can be traveled with the engine off.
- Energy diversification, since electricity can be generated from a variety of renewable and non-renewable energy sources.
- Reduced petroleum dependence, since electricity is typically not generated from petroleum.

The traditional operating concept for grid-charged HEVs aims to provide a large all-electric-range (AER) capability for the initial portion of a driving trip. This approach delays the production of vehicle cold-start emissions, and since the majority of trip lengths are relatively short (e.g., < 40 miles), it is possible that many trips can be completed without the engine turning on at all [1]. This is an important benefit in California, for example, where the vehicle can qualify for zero emissions vehicle (ZEV) credits.

However, the traditional AER-based operating concept for grid-charged HEVs results in challenging technical requirements for the energy storage system (ESS). In particular, it dictates a requirement of simultaneously high energy storage and power capability in the ESS, which has implications for the cost, size, weight, and lifetime of the battery. Other HEV operating concepts can still provide the net-discharge that is characteristic of a grid-charged HEV, but with reduced battery power requirements that might enable the use of less costly and/or smaller batteries.

Therefore, the objectives of this paper are to:

1. Calculate ESS power and energy requirements for grid-charged parallel HEVs with different operating strategies
2. Consider implications for the rest of the system (in particular, engine operation and efficiency, and vehicle fuel economy and emissions).

GRID-CHARGED HEV TECHNOLOGY

A variety of terminology exists to describe grid-charged HEVs and their components, and it is important that consistent definitions are used.

In this paper, the term "grid-charged HEV" is used to describe an HEV that can be recharged from the electrical grid. This allows for some miles to be traveled using electrical energy stored onboard, with the remaining miles traveled using chemical energy stored in the fuel within the vehicle tank (typically gasoline). Equivalent terminology for a "grid-charged HEV" includes "charge-depletion HEV" and "plug-in HEV." The terminology HEV*X* is also used regularly to describe a grid-charged HEV with useable electrical energy storage capacity equivalent to *X* miles of travel. However, grid-charged HEVs should not be confused with the vehicle-to-grid (V2G) concept, in which electric-drive vehicles (not just HEVs) can provide value to electric utilities through peak shaving and ancillary services [2].

When describing the ESS in an HEV, a useful metric is the power-to-energy ratio (P/E), defined as:

$$P/E\left(\tfrac{1}{h}\right)=\frac{power(kW)}{energy(kWh^{*})}=\frac{specific\ power\left(\frac{W}{kg}\right)}{specific\ energy\left(\frac{Wh^{*}}{kg}\right)}=\frac{power\ density\left(\frac{W}{L}\right)}{energy\ density\left(\frac{Wh^{*}}{L}\right)}$$

The P/E ratio has units of (1/h) and relates the suitability of an ESS component to power events with different timescales. When quoting or calculating a P/E ratio, it is important to refer to the *useable* energy storage in the ESS (noted by the asterisk *) as different technologies may be cycled within different state-of-charge (SOC) envelopes designed to preserve their operating lifetime.

Energy Storage System Requirements for Grid-Charged Parallel Hybrid Electric Vehicle

The traditional AER-based operating concept for grid-charged HEVs results in quite challenging technical requirements for the energy storage system. First, the battery will require a relatively large amount of useable energy storage to provide sufficient AER. Second, the battery requires a relatively large peak power capability so that engine operation can be avoided without compromising vehicle performance or drivability. As an example, this paper considers the mid-size sedan platform used in grid-charged HEV studies performed by the Electric Power Research Institute (EPRI) [1]. Relevant technical parameters for this vehicle platform are presented in Table 1.

TABLE 1
Technical Specifications for the EPRI Grid-Charged HEV Mid-Size Sedan

Drag-area (C_DA)	0.71 m^2
Rolling resistance coefficient (C_{RR})	0.008
Accessory load (electrical)	500 W
Test mass	1700 kg (approx.)
Peak Power requirement, based on: • 0-60 mph in 9.5 s • 50-70 mph in 5.1 s	115 kW (approx.)
Continuous power requirement, based on: • Top speed of 90 mph • 7.2% gradeability at 50 mph	45 kW (approx.)
Electrical energy consumption	300 Wh/mile (approx.)

Using the vehicle parameters in Table 1, Table 2 presents the calculated energy storage requirements for several grid-charged HEV variants (HEV10, 20, and 60). Two data sets are presented—one assuming that the internal combustion engine (ICE) never comes on during electric-only operation (labeled “no ICE assist”), and another assuming the engine can be turned on to supplement the battery power if necessary (labeled “with ICE assist”). In this example, the engine was assumed to be sized to the minimum continuous power requirement of 45 kilowatts (kW).

Table 3 presents some present-day battery products [3, 4] to compare to the calculated P/E ratios in Table 2. First, we note that the high-energy, electric vehicle (EV) cells match well with the requirements for the HEV60, and the mid-range cells are well suited to the HEV20. In contrast, the high-power (HEV) products are limited by their small useable kilowatt-hour (kWh) ratings, making them relatively unsuited to grid-charged HEV applications.

TABLE 2
Hypothetical Battery Specifications for Different Variants of the EPRI Grid-Charged HEV Mid-Size Sedan

	No ICE assist			With ICE assist (45 kW)		
	Power (kW)	Energy (kWh)	P/E (l/h)	Power (kW)	Energy (kWh)	P/E (l/h)
HEV10	115	3.0	38.3	70	3.0	23.3
HEV20	115	6.0	19.2	70	6.0	11.7
HEV60	115	18.0	6.4	70	18.0	3.9

However, the data in Table 3 also demonstrates trade-offs in battery design that result from differing P/E requirements—in particular, the compromises involved in designing a battery to be simultaneously capable of high energy and power. Note that the specific energy (Wh/kg) and energy density (Wh/L) of the mid-range batteries are lower than that of the high-energy batteries, while their specific power (W/kg) and power density (W/L) are lower than that of the high-power products. Similarly, we would expect the mid-range battery costs to be higher than the high-energy and high-power products, in $/kWh or $/kW terms, respectively. In some cases, the differences are quite marked. For example, the energy density of the Cobasys 4500 (mid-range) module is almost half that of the Cobasys 9500 (high-energy) module.

These findings lead to a few important questions:

1. Instead of the traditional AER-based strategy discussed so far, are there other operational concepts for grid-charged HEVs that can enable the use of less costly, smaller and lighter battery packs in grid-charged HEVs?
2. If different operating strategies are employed, what implications are there for the rest of the system—in particular, engine operation and efficiency, and vehicle fuel economy and emissions?

This paper considers an alternative “electric-assist” operating strategy and discusses the implications this has for battery size and vehicle fuel economy.

Battery/Engine Sizing Trade-Offs in Grid-Charged HEVs

Fig. 1 maps out the grid-charged HEV design space for the EPRI sedan in terms of engine power and battery P/E ratio. It also includes high-energy and mid-range battery technologies from Table 3. This plot can be used in several ways:

1. Beginning with an electric range target and a known battery technology (P/E), the chart suggests what engine size to use. For example, for an HEV20 using mid-range SAFT VLM 27 cells, a 55kW engine is well suited.
2. Beginning with an electric range target and a known engine size, the chart suggests what battery technology (P/E) is required. For example, for an HEV20 using an 85kW engine, the high-energy Cobasys 9500 modules are well suited.

TABLE 3
PRESENT-DAY BATTERY PRODUCTS FOR EVS, HEVS, AND GRID-CHARGED HEVS [3, 4]

Battery	Wh/kg	Wh/L	W/kg	W/L	Useable SOC	P/E
High Energy (for Evs)						
SAFT VLE 45 cell	149	313	664	1392	~80%	5.6
Cobasys 9500 module	60	155	250	650	~80%	5.2
Mid Range (for grid-charged HEVs?						
SAFT VLM 27 cell	124	252	987	2000	~80%	9.9
Cobasys 4500 module	45	87	605	1180	~80%	16.8
High Power (for HEVs)						
SAFT VLP 20 cell	89	187	1413	2973	< 20%	>79
Cobasys 1000 module	43	83	1100	2200	< 20%	>128

3. Finally, note that an ideal solution does not always result from these procedures. For example, for an HEV60 using a 45kW engine, a P/E ratio of approximately 4 is required but none of the technologies in Table 3 have this capability. Use of any one of the batteries from Table 3 would result in a) a battery with the required energy storage but excess power, or b) a battery with the required power but insufficient energy storage to achieve the HEV60 electric range.

When considering trade-offs in the relative sizing of the battery and engine, the first thing to note is that the analysis presented so far has assumed the engine will be of minimum size (45 kW continuous). However, a larger engine (with a correspondingly smaller battery) can be employed without compromising vehicle performance, while still providing for the requisite number of EV miles. Under this alternative approach, the engine might be utilized throughout all trips, with the battery supplementing the engine via an "electric-assist" control strategy designed to produce a net-discharge of the battery over time. (We have deliberately shifted terminology from AER to EV miles to recognize that the engine may now be utilized throughout the trip.)

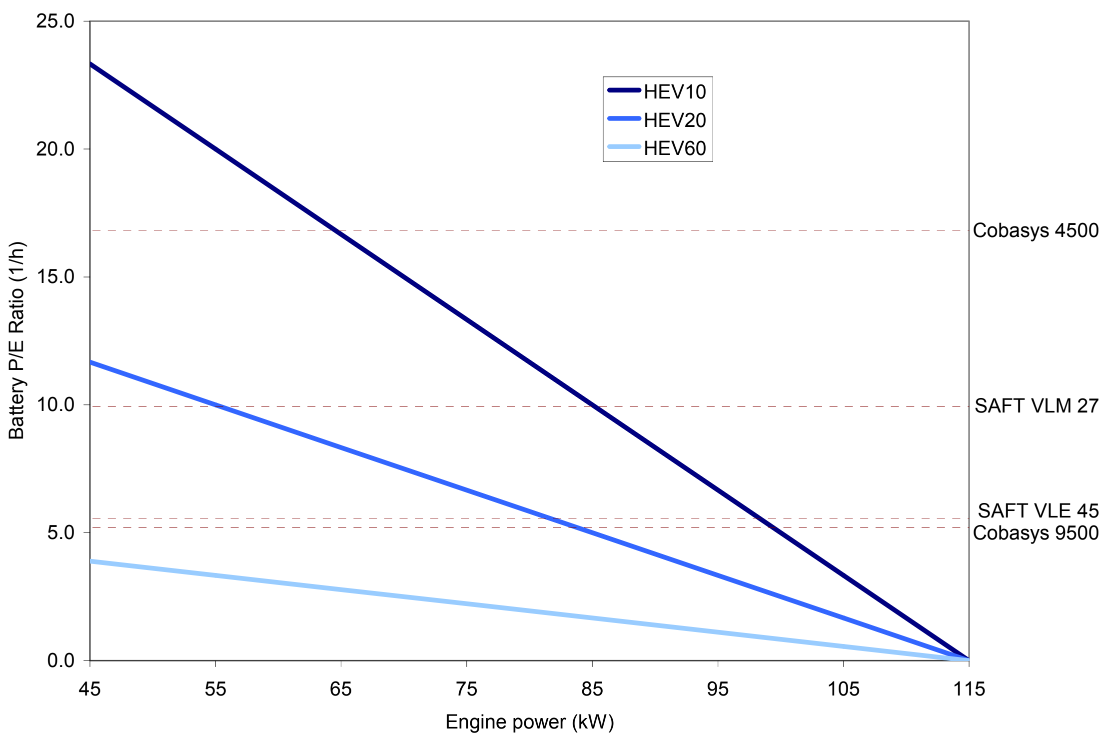

Fig. 1. The grid-charged HEV design space for the EPRI mid-sized sedan.

TABLE 4
FOUR HYPOTHETICAL BATTERY SYSTEMS FOR THE EPRI HEV20 MID-SIZE SEDAN

Battery	Total Power (kW)	Battery Energy (Useable) (kWh)	Battery Mass (kg)	Battery Volume (L)	Battery Power (kW)	Engine Power (kW)
Lithium-Ion						
SAFT VLM 27 cell	115	6.0	61	30	60	55
SAFT VLE 45 cell	115	6.0	50	24	33	82
Nickel-Metal-Hydride						
Cobasys 4500 module	115	6.0	167	86	101	45
Cobasys 9500 module	115	6.0	125	49	31	84

For example, consider the hypothetical HEV20 mid-size sedan, for which the required total peak power is 115 kW and required useable energy storage is 6.0 kWh (based on 300 Wh/mile). Table 4 presents four different combinations of engine/battery size, based on a pair of high-energy and mid-range battery products for both lithium-ion (Li-Ion) and nickel-metal-hydride (NiMH) technology. For each battery selection, the 6.0 kWh of energy storage is used to calculate battery mass, volume, and power (using data from Table 3). The engine power is then calculated as the difference between the battery and required total power (subject to the 45 kW continuous minimum). In both high-energy cases (the SAFT VLE 45 and Cobasys 9500), the engine is significantly larger than in the mid-range case. Furthermore, note that the battery mass and volume are significantly smaller for both high-energy cases. We would expect the high-energy variants to be less costly too, based on lower specific energy costs ($/kWh).

However, the reduced power capability of the high-energy batteries (33kW for Li-Ion, 31kW for NiMH) has implications for the vehicle operation and control strategy. First, the reduction in battery power sacrifices the vehicle's all-electric capability and limits the opportunity for regenerative braking. Figure 2 shows a histogram of power requirements for three driving cycles: the UDDS (Urban Dynamometer Driving Schedule) and HWFET (Highway Fuel Economy Test) used for US government fuel economy and emissions testing and the US06 (a higher speed, higher acceleration cycle). In each cycle, the peak positive power greatly exceeds 30 kW meaning that the engine would have to turn on to follow the cycle. Furthermore, in the US06

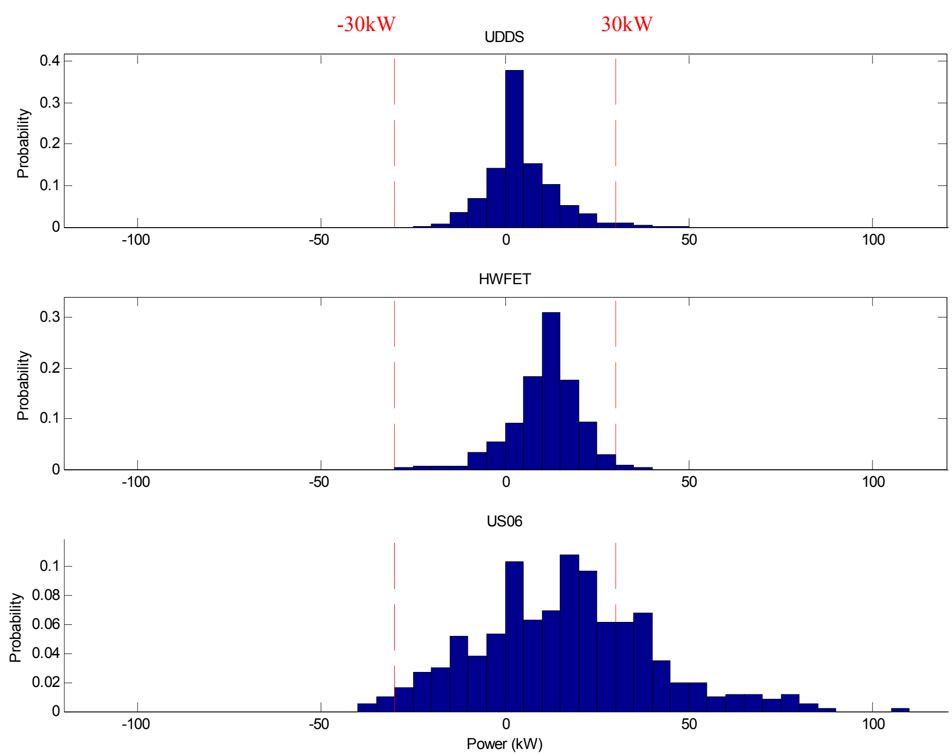

Fig. 2. Histograms of power requirements for the UDDS, HWFET, and US06 driving cycles.

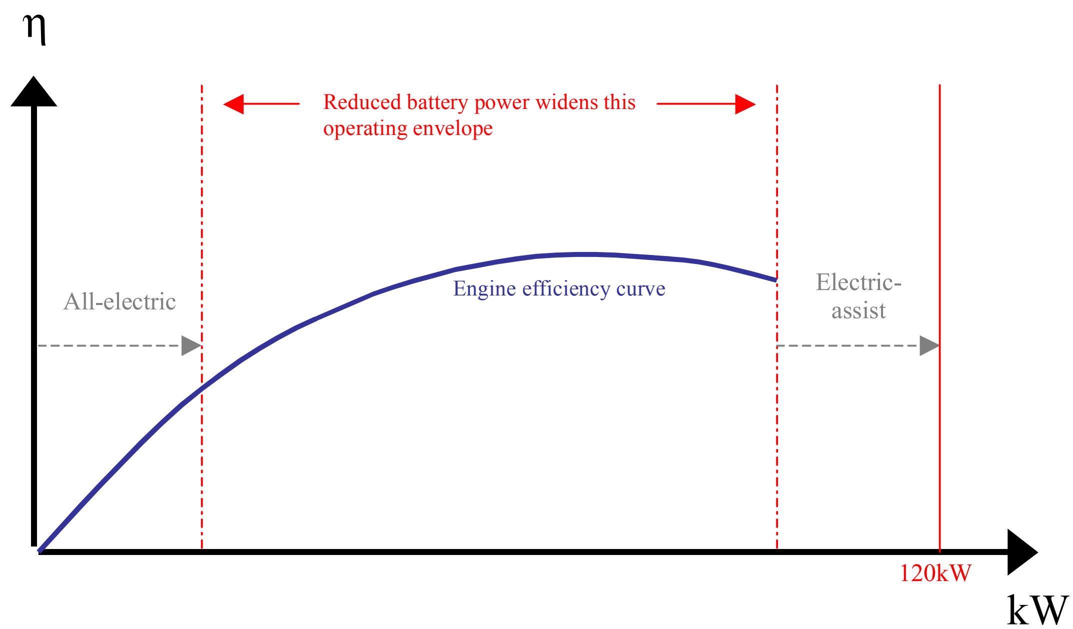

Fig. 3. The relationship between battery power and engine operating efficiency.

cycle, the peak negative power exceeds 30 kW, which means that friction (as opposed to regenerative) braking would be inevitable. It should also be noted that high-energy batteries exhibit a relatively lower receptiveness to pulse charge power produced by regenerative braking, and this could create a constraint on all driving patterns.

Second, with their smaller powers, the high-energy batteries have a lesser ability to load-level the engine and maximize its fuel efficiency. Figure 3 demonstrates how the reduction in battery power forces the engine to operate over a wider power range, which results in operation at points of lower fuel efficiency. Furthermore, we would expect the high-energy batteries to cycle power less efficiently than the mid-range types, leading to a further reduction in net vehicle efficiency.

Finally, the lower peak power of the high-energy batteries will result in typical operation closer to, or at, their peak current limits, which has the potential to accelerate battery wear and reduce lifetime.

Conclusions and Future Work

This paper has discussed the energy storage requirements for grid-charged parallel HEVs using different operating strategies.

Under the traditional AER-based operating concept for grid-charged HEVs, it has shown that P/E ratios for present-day, high-energy and mid-range battery products match the P/E requirements for grid-charged HEVs. However, the simultaneous requirement for high energy storage and peak power capability in the battery can result in packs that are larger and more expensive due to compromises in the cell design to meet this goal.

Therefore, this paper proposes an alternative operating concept for grid-charged HEVs that use a larger engine to enable the use of smaller, less-costly batteries. Our analysis demonstrates that this alternative approach can be implemented using current high-energy battery technology. However, the increased engine size and reduced battery power have several probable drawbacks: 1) sacrificed all-electric capability and limited regenerative braking; 2) reduced engine operating efficiency; and 3) accelerated battery wear and reduced lifetime. Overall, the implication is for a potential reduction in vehicle efficiency during both charge-depleting and -sustaining operation.

From these conclusions, a number of questions arise for further exploration:

- How much is the vehicle efficiency reduced by using a smaller battery?
- To what extent is the reduction in motor and battery mass and volume offset by the increase in engine mass and volume?
- What type of control strategy suits the reduced ESS grid-charged HEV concept?
- Can the impact on battery life be quantified?
- How do the P/E requirements of V2G affect the system requirements, and how might V2G cycling affect the battery life?
- As an alternative to the reduced ESS concept, might a "hybrid" or "dual-source" ESS using ultra capacitors and high-energy batteries make a good

alternative to mid-range batteries in grid-charged HEV applications?

- What are the optimum ESS requirements for various grid-charged HEV configurations?

National Renewable Energy Laboratory researchers will consider each of these issues in their future work.

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